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# Assessing the resilience of potable water supplies in Southeast Queensland Australia

Paul Barnes,
QUT Business School, Queensland University of Technology
p.barnes@qut.edu.au
Pradeep Amarasinghe,
Faculty of Built Environment and Engineering, Queensland University of Technology
p.amarasinghe@qut.edu.au
Prasanna Egodawatta,
Faculty of Built Environment and Engineering, Queensland University of Technology
p.egodawatta@qut.edu.au
Ashantha Goonetilleke,
Faculty of Built Environment and Engineering, Queensland University of Technology
a.goonetilleke@qut.edu.au

## Abstract

Historically, cities as urban forms have been critical to human development. In 1950, 30% of the world's population lived in major cities. By the year 2000 this had increased to 47% with further expected growth to 50% by the end of 2007. Projections suggest that city-based densities will edge towards 60% of the global total by 2030. Such rapidly increasing urbanisation, in both developed and developing economies, challenges options for governance and planning, as well as crisis and disaster management. A common issue to the livability of cities as urban forms through time has been access to clean and reliable water supply. This is an issue that is particularly important in countries with arid ecosystems, such as Australia.

This paper examines preliminary aspects, and theoretical basis, of a study into the resilience of the (potable) water supply system in Southeast Queensland (SEQ), an area with one of the most significant urban growth rates in Australia. The first stage will be to assess needs and requirements for gauging resilience characteristics of a generic water supply system, consisting of supply catchment, storage reservoir/s and treatment plant/s. The second stage will extend the analysis to examine the resilience of the SEQ water supply system incorporating specific characteristics of the SEQ water grid made increasingly vulnerable due to climate variability and projected impacts on rainfall characteristics and compounded by increasing demands due to population growth. Longer-term findings will inform decision making based on the application of the concept of resilience to designing and operating stand-alone and networked water supply infrastructure systems as well as its application to water resource systems more generally.

**Keywords:** Resilience, Resilient infrastructure systems, Potable water supplies, Southeast Queensland

# 1. Introduction

## 1.1 Background

Water supply and sanitation are among the most basic human needs and a reliable potable water supply is a key measure of human well-being. The main objective of a water supply system is to supply good quality water reliably to the consumers. The functions of a water supply system depend on complex interactions between natural phenomena and human influences. A generic water supply system consists of a supply catchment, storage reservoir, and a treatment plant. Water supply systems are influenced by diverse systems characteristics with varying levels of complexity. The system characteristics vary from geographical region to region due to differences in catchment characteristics, differences in climatic conditions and differences in demand and supply scenarios. It is essential that these diverse and highly variable factors are taken into consideration to enhance the reliability of the system and service standards.

A further complexity arises due the dynamic nature of the various system characteristics that influence a water supply system. Climate change and population growth are two important factors which can influence the characteristics of a water supply system and thereby the reliability of supply and in turn the resilience of the system. The predicted consequences of climate variability, such as the increase in temperature, changes in precipitation patterns and intensity, runoff, evaporation and soil moisture will exert a significant influence on changing the system properties. Population growth will not only increase the water demand, but will also change the demand characteristics. Furthermore, increased urbanisation such as the construction of roads and buildings and more land usage for industrial purposes will in turn increase the pollution of receiving water bodies. Therefore, climate change and population growth have a direct impact on the quality and quantity characteristics of water available for supply. To withstand these pressures, the system needs to be highly resilient.

It is difficult to identify how the consequences of climate change, such as changes in temperature and rainfall parameters will affect the catchment properties, which in turn will influence the availability and quality of water in the supply source. Water quantity reduction and quality deterioration issues will influence the degree of resilience of the water supply system. Analysis of water supply system resilience influenced by changes in natural and human influences is not common practice, and is not explicitly taken into account.

In summary, the pressures due to natural and human influences may adversely affect the availability and quality of water in supply systems. It is in this context, that the concept of resilience needs to be applied to a water supply system. In order to ensure the reliability of supply of good quality water to a region, the degree of resilience of the water supply system should be high. Resilience is a concept that can be used to assess the capability of a system to maintain the operational functionality within design parameters, when placed under stress. A resilient system has the ability to cope with unfavourable forces acting on the system without going into failure state and if a failure event occurs, it should have the ability to reorganise to recover and the adaptive capacity to continue its functions satisfactorily.

To date, water resource issues have not been adequately addressed in climate change analyses and, climate variability problems have not been adequately dealt with in water resources analyses, management and policy formulation (IPCC 2008). Therefore, it is necessary to improve our understanding of the relationships of water quality and quantity issues related to consequences of climate variability and population growth in order to formulate better water management practices.

## 1.2 The Australian and Southeast Queensland Context

Australia has a dry and relatively arid climate with 80% of the land having annual rainfall less than 600 mm and 50% having less than 300 mm (Bureau of Meteorology 2011). The rainfall patterns across Australia are highly seasonal making water availability a key issue. Potable water supply systems across Australia are largely dependent on water storage reservoirs fed by rainfall and storm water runoff. It is in this context that the impacts of climate change, which is predicted to increase temperatures and sea levels, and significantly alter rainfall patterns needs to be viewed. In Australia, climate change is expected to result in longer periods of dry weather with fewer, but more intense, storms (CSIRO 2007).

Temperature is directly associated with droughts. Nicholls (2004) investigating the changing nature of droughts in 1982, 1994 and 2002, noted that according to modelling experiments done by Rind (2000), the increase in moisture demand will outweigh the increase in precipitation, leading to an increase in droughts. Australia is one area where Rind's Model experiments predicted an increase in droughts in an enhanced greenhouse situation. Therefore, there is no doubt that global warming has a direct impact on climate change at the regional scale increasing atmospheric and surface temperature associated with the increase in frequency and severalty of droughts. The combination of decreased rainfall, higher temperature and evaporation, increase in solar radiation and decrease in cloud cover will result in increased evaporation and a consequent decrease in water levels in water storages.

Trends in extreme daily rainfall vary across Australia. Considering the regional variation of rainfall across Australia, CSIRO (2007) has highlighted the following significant observations. North West Australia has had an increase in annual rainfall since 1950. Eastern and South Western Australia has become drier since 1950. New South Wales and Queensland had very wet period around 1950s but unusually dry in recent years. Across Victoria, very wet 1950s and an extremely dry last decade was observed. These variations in rainfall patterns are hypothesised to be the result of global warming associated with greenhouse effects.

Considering Southeast Queensland (SEQ), the impacts of population growth are very significant. SEQ is 22,420 $km^2$ in extent and accounts for two-thirds of the total population in Queensland. For the five years from June 2004 to June 2009, the average annual population growth rate for Queensland was 2.6% per year, making it the fastest growing Australian state or territory for that period (Bureau of Statistics 2011). This translates to a population increase by about 50,000 per annum for the last ten years, with a further one million people expected to move into the region over the next twenty years (OUM 2005). From June 2008 to June 2009, the population increased by 80,900, accounting for 69% of the total growth in the State (Bureau of Statistics 2011). As SEQ population continues to grow, forecasts show that the projected population in 2056 will be between 5,696,300 (medium series) and 7,014,700 (high series) (Queensland Water Commission 2011).

The water supply network for Southeast Queensland is the SEQ Water Grid. It provides two-way pipeline network to connect major bulk water sources in the region to facilitate water from areas of surplus to be moved to areas that face a shortfall. The Water Grid allows water supply to be managed at a regional level rather on a storage basis. The Water Grid enables better co-ordination of delivery of urban and industrial water supplies across the SEQ region by connecting the major water supply sources, treatment plants and bulk water transport networks (Queensland Water Commission 2011).

South East Queensland Water Grid obtains water from different water supply sources. These sources are dams, a desalination plant, groundwater sources and the Western Corridor Recycled Water Scheme. Regional interconnector pipelines have been built to allow water from new and existing water sources to be moved around the Grid. In order to optimise the benefits of the SEQ Water Grid, a coordinated institutional structure has been established to prevent fragmentation.

Stormwater runoff is one of the catchment characteristics that will be influenced by variations in rainfall. As a result of the increase in temperature, more evaporation will take place from soil and plants resulting in reduced flow into rivers and aquifers. Also, the rate of evaporation from the reservoir open water surface may increase, thereby reducing the active storage volume. CSIRO (2007) notes that rainfall decline has a major impact on the reduction in surface water available for storage. For example, inflows to the South West Western Australian integrated Water Supply system has been significantly reduced from 1911 to 2005. Victoria has experienced a 20% decease in rainfall since the mid 1990s, resulting in inflow reduction of about 40%. For every 1% rainfall decrease, the percentage reduction in inflows is far greater, and this factor grows as the dry conditions increase (CSIRO 2007). According to simulations undertaken by Chiew and McMahon (2002), stream flow in the Northeast and East Coast of Australia could change by -5 to +15% and ±15% respectively by the year 2030. The annual runoff for South Eastern Australia could decrease by up to 20%.

Queensland Water Commission (2011) has shown that mean temperatures in the Western parts of SEQ could increase by between 0.8°C and 1.2°C, and accordingly evaporation could increase by 2% to 8%, and annual rainfall could reduce by 5% or increase by 20%. Even small changes in climate could have significant impacts on water resources.

Analysis of the resilience of Southeast Queensland water supply system entails the investigation of several sub systems (catchments and supply sources). Taking into account the climate variability and the population growth in SEQ, the specific areas of research investigation are:

- How do catchment properties change and what is the impact on quality and quantity of water in the reservoir supply source due to the pressures of climate change and population growth?

- What approaches allow assessing the resilience of the water supply system in SEQ under the pressures of climate variability and population growth?

The assessment of these issues will of course require detailed analysis and establishment of a range of databases and, arguably, new approaches to dealing with resilience. Notwithstanding the immediacy of these questions there are a number of significant theoretical and practical issues that require investigation towards addressing them. This paper seeks to establish the context for these endeavours and establish conceptual approaches to applying the key concept of resilience across what is ostensibly new territory; linked ecological/biological and socio-technical systems.

## 1.3 Resilience (in Engineered Systems)

Resilience defines the ability of a system to maintain its operational functionality under stress. In order to study systemic resilience it is important to define its use in relation to complex systems. Definitions of resilience vary. Dekker and Hollnagel (2006) have interpreted systemic resilience as the ability to recognise, absorb and adapt to disruptions that fall outside a system's design base. A similar definition by Cox (2008), suggests that a resilient system has a high adaptive capacity and is able to withstand disturbances without a decline in crucial functions.

Wong and Blackmore (2009) have classified three aspects of resilience as follows:

- Resilience for adaptive capacity and management.
- Resilience against crossing a system performance threshold;
- Resilience for system response and recovery after negative aspects.

They have further illustrated the above definitions in Table 1, which provides a more detailed coverage of the resilience concept. While the concept of resilience can be very broad, resilience as used in this study relates to the capacity of a system to withstand adverse pressures (multi-source) and recover from failure events or other significant disturbances. When it comes to complex systems, failures are not uncommon events. A central characteristic of a resilient system is to withstand internal or external adverse forces and recover from the unsatisfactory state and bounce back to the original state or to a desirable state when affected by adverse forces. A resilient system consists of avoidance, survival and recovery features that will help to continue operation under stress. Therefore, the assessment of system resilience will allow formulation of better management procedures for the system.

In what is ostensibly a generic systems approach to resilience (Madni and Jackson 2009), failure is seen as the inability to perform necessary adaptations to cope with real world complexity, rather than as breakdown or malfunction. Therefore, a resilient system needs to continually adjust to changing conditions. Success depends on the ability of the system to adapt to changes and new developments. Such capabilities will reduce the likelihood of significant function-changing failure due to the stresses acting on the system. Madni and Jackson (2009) suggest that 'resilience engineering' is based on four key pillars: disruptions, system attributes, methods and metrics (Figure 1).

*Table 1: Concepts of Resilience (after Wong and Blackmore 2009)*

| | *Resilient* Capability | | |
|---|---|---|---|
| *Attributes* | *... For adaptive capacity/management* | *... Against regime change* | *... For response/recovery* |
| *Definition* | Ability to pre-empt and avoid major mishaps in institutions | Magnitude of disturbance that can be absorbed without flipping into an alternative state | Speed or rate of system recovery after disturbance |
| *Objectives* | Reducing incident and accident occurrences and impact if occurred in institutions | Positioning the system in a favourable regime (original or alternate) | Returning the system to an operational status in the original regime |
| *Emphasis* | Proactively monitoring the effects of existing management and operational approaches | Persistence, change, unpredictability | Efficiency, constancy, predictability |

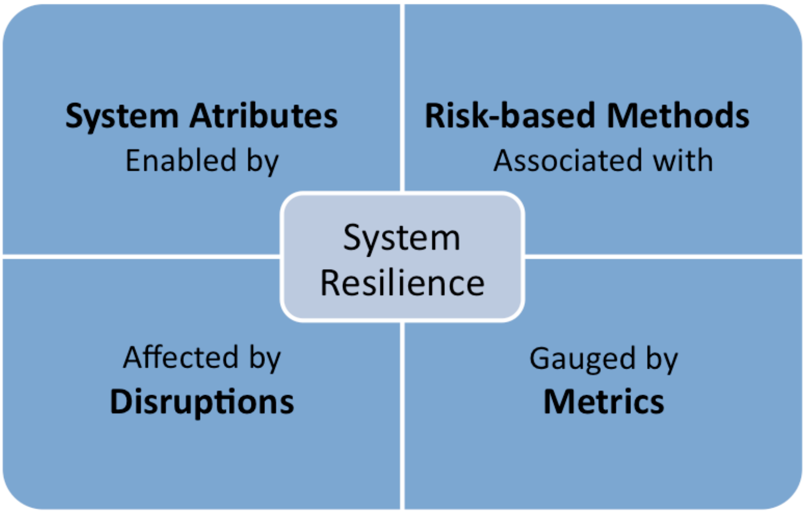


Figure 1: Drivers of System Resilience (after Madni and Jackson 2009)

Functionality of the system is associated with methods that include conventional risk assessments, safety measures, utility cost tradeoffs, integrative/holistic methods and ongoing proactive risk management processes. Finally the degree of resilience is gauged by selected metrics.

## 1.4 Resilience: (in Biological Systems)

From a natural systems perspective, resilience is defined as the capacity of a system to actively re-organise itself and maintain functionality and output, while absorbing a disturbance (Walker et al. 2004). While very similar to the engineering definition, biological applications differ slightly to encapsulate the amount of disturbance a system can absorb without shifting into an alternate operational regime with subsequent changes in function and structure. More resilient a system, the larger the disturbance it can absorb without shifting to an alternate regime (Walker et al., 2006). Applied in this sense, resilience is linked inexorably to notions of persistence and sustainability.

Early studies of resilience in the biological context emerged from ecological analyses of predator-prey relationships (Holling, 1973). However, its viability as an analytical concept applied to wider settings has become important in recent times. Similarly, Folke (2006) details other examples of resilience-focused research such as: Social resilience relation to coastal communities and their exposure to natural hazards (Adger, 2000); vulnerability of cities (Pelling 2003); patterns of migration (Locke et al. 2000); management processes in institutions and theories of social change (Holling & Sanderson 1996; Westley 2002); famine and assessment of vulnerability of food systems (Fraser 2003; Fraser et al. 2005); and, the emergence of tipping points and multi-stable behaviour of social systems (Brock 2006).

A key characteristic in any approach to systemic resilience is stability. Table 2 contrasts a range of base concepts, their characteristics, focus and context in ecological and socio-ecological systems.

Each base concept varies with the type of system and the nature of the interaction of sub-components. The socio-ecological category represents interdependencies between humans, their systems (i.e. economies, legal frameworks, agricultural practices) and the wider biological environment. Relationships between components within this category are dynamic with considerable scope for complexity across a range of spatial, temporal and social scales: thus emphasis on adaptability, innovation and learning.

*Table 2: Resilience: From technical to a broader Social - Ecological contexts (After Folke, 2006)*

| *Systems concept* | *Characteristics* | *Focus* | *Context* |
|---|---|---|---|
| Ecological | Buffer capacity to absorb shock & maintain function | Persistence, robustness | Multiple stability landscapes |
| Socio-technical | Interplay disturbance & reorganization, sustaining & developing | Adaptive capacity transformability, learning, innovation | Integrated system feedback, dynamic interactions |

While the treatments of resilience within ecological systems contrast to the co-evolutionary aspects of interdependent socio-ecological views and emphasise environmental stability, there remains the context of alternate functional regimes that may appear after an external disturbance.

An important concept related to resilience in ecological systems is a ‘threshold’ of change. For example, an ecosystem might absorb disturbance stresses and resist change but over time stability decreases (sub-system processes) and a process where functionality changes and the regime shifts to another form. Kinzig et al. (2006) give an example of an agricultural ecosystem - a grassy savannah where cattle are grazed. With increased grazing pressure grass levels become slightly depressed but may still remain effectively a grassy savannah. There is a (regime) shift towards a different foliage cover – with a higher concentration of shrubs, if grazing continues and reaches a particular critical point and this state is suddenly lost. Thus the transition, while not sudden has passed through a threshold (a functional buffer) resulting in a general condition where a significant change occurred in the ecosystem. Given the complexities of threshold phenomena in natural systems, the models are often more descriptive than those used in engineering applications.

# 2. Challenges to the Enquiry

## 2.1 Merging Concepts and Merging Domains

The initial approach taken here is to consider application of the concept of resilience across three significant and different domains: water catchments, and a growing urban environment (that includes a variety of land use modes common to a high-growth region), facilitated by a complex system built infrastructure networks. The long-term viability of a catchment area can be impacted by many sources of disturbance, ranging from natural (weather and fire) to human sourced problems (urbanisation and land use planning). The continuity of supply will impact the capacity to supply and re-supply reservoirs. Equally critical are options for when to build new reservoirs and related supply-side infrastructure. The third factor, on the demand side, is consumption. All three elements form a meta-system. As depicted in Figure 2, any careful assessment of resilience of supply for potable water requires the inclusion of three domains as key aspects for consideration.

Additionally, factors that can impede resilient functioning of such complex, wide-area infrastructure systems include failure to fully understand the *interconnectedness* of components and the *asymmetric* effect of unconventional failure modes – made possibly more likely due to the interdependencies. A further complication is that while engineering and ecological approaches to resilience have been examined in some depth within relevant literature, the integral aspects of this meta-system have not.

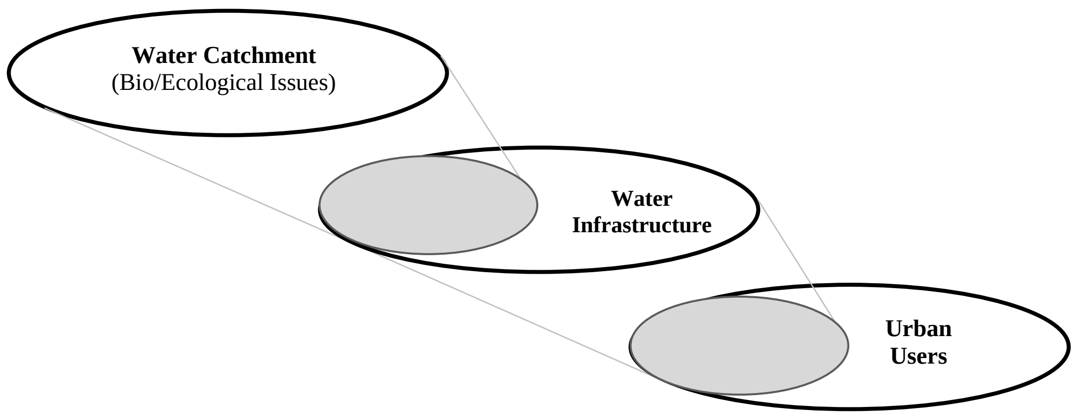


Figure 2: Interdependent Domains as a meta-system

How might the relationships between the three domains shown in Figure 2 above be described: within the broad context of variable climate factors? For example, would predictions (or the reality) of less rainfall signal the consideration of options to build more reservoirs or change the way in which water is delivered to urban users? How should water management practice and policy at an end-user level be also factored into consideration in the overall management of the other domains? In an ideal approach encompassing a complete potable water meta-system, sensitivity to interdependencies of each domain should be paramount.

## 3. **What might be done** (Problem *Taming* or Problem *Definition)*

The need to accurately assess the impact of climate variability is by itself a difficult issue, let alone detailing technical considerations encompassing the meta-system depicted in Figure 2. Further, the topic is a highly complex policy issue involving multiple causal factors of climate threats and high levels of disagreement about the nature of the problem and the best way to tackle it. As a significant policy issue, it easily fits the description of a 'wicked' problem (Commonwealth of Australia 2007).

The term 'wicked' in this context is used describe issues or problems that are highly resistant to resolution in contrast to 'tame' problems (Rittel and Webber 1973). However, a tame problem might be quite complex, but remains one that can, with effort, often be resolved. Wicked problems are often not stable with the constraints or evidence involved in understanding the problem (e.g., scientific evidence, resources, public and private opinion), widely ambiguous and open to wide conjecture.

A central issue to the work introduced in this paper is recognition that modelling resilience and continuity of supply of potable water supply in the face of climate variability requires a radically different approach than that detailed in much of the extant literature. Not only are extant published models narrow in their application of available definitions of resilience, the domains over which analysis and assessment must travail are far more complex than implied in published work.

## 4. Critical Steps

A common basis of the argument in this paper (and across relevant literature) is that resilient systems have the capacity to re-organise or adapt to threats or interruptions to internal or external operating environments and to maintain key functions following significant disturbances. Such capacities are of the highest importance for nationally relevant infrastructure systems with high social value such as water supply systems. High reliability, as a sub-function of resilience, is particularly important in the provision of infrastructure supporting essential services. The argument put forward in this paper is that planning and managing potable water supplies in a climate variable future requires application of resilience thinking across three interdependent domains: biological, built and socio-technical.

Contingency and crisis management capabilities are critical assets for both public and private sector infrastructure operators. Such capabilities, as part of institutional and organisational response to non-routine events, may be categorised as:

- **Prevention:** ensuring infrastructure is built to regulated standards and managed effectively both as standalone domains and as connected domains;

- **Preparation:** planning for the known and possible instances of failure, disturbance, variability within either of the domain layers;

- **Response:** recognising emergent crises and ensuring timely responses (some of which are likely to be different in each domain); and

- **Recovery:** restoring normal functioning and applying adaptive strategies in all domains, as needed.

However, both *preventing* and *preparing* for crises presumes a deep and effective understanding of the way in which ‘unknown – yet knowable’’ factors and conditions can cause loss and how such factors directly or indirectly exploit organisational vulnerabilities. *Responding* to and *recovering* from crises also assumes an appreciation of mitigation options and consequence assessments.

The ongoing research effort described here has as a core enabler a requirement to scope crisis management needs/functionality across the range of industrial, urban and natural settings inherent to the provision of potable water supplies. In pursuing this it will develop practical frameworks to assist in identifying resilience concepts applicable to the operation and protection of diverse systems of built infrastructure. It seeks also to identify and define how strategic approaches to crisis planning, applying resilience concepts into the design and operation of critical infrastructure components, can enhance the efficiency and effectiveness of emergency response and recovery.

Developing a comprehensive architecture or framework for interdependency modelling and simulation is a major challenge. Many models and computer simulations exist for aspects of individual infrastructure (e.g., load flow and stability programs for electric power networks, connectivity and hydraulic analyses for pipeline systems, traffic management models for transportation networks), but simulation frameworks that allow the coupling of multiple interdependent infrastructure to address infrastructure protection, mitigation, response, and recovery issues are only beginning to emerge (Rinaldi et al. 2001:23).

Metrics that describe the operating states of interdependent infrastructure and scale of interdependency-related disruptions are sorely lacking. These metrics should include a range of economic, social, and national security considerations. Such quantitative measures could be used to validate models and simulations through comparisons to real-world data; to develop a baseline and analyse historical data; and to prioritise interdependency-related vulnerabilities, threats, and risks. The metrics would need to be:

- Relevant to the effects they seek to measure;
- Suitable for use in developing data sets;
- Suitable for use in running and validating models;
- Helpful in prioritising threats and risk estimates;
- Suitable for comparing and measuring alternative managerial options across domains.

Currently, there is no satisfactory set of metrics or models that articulate the likelihood of failure, either naturally caused or human induced, for highly interdependent infrastructures. (Rinaldi

2001:24). Equally under represented are theoretical bases for resilience in such systems. As part of our on-going research we hope to create knowledge in relation to water supply systems.

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